AGN FEEDBACK AND EVOLUTION OF RADIO SOURCES: DISCOVERY OF AN X-RAY CLUSTER ASSOCIATED WITH Z=1 QUASAR

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ABSTRACT

We report the first significant detection of an X-ray cluster associated with a powerful (L$_{bol}$ $\sim 10^{47}$ erg sec^{-1}) radio-loud quasar at high redshift (z=1.06). Diffuse X-ray emission is detected out to $\sim$ 120 kpc from the CSS quasar 3C 186. A strong Fe-line emission at the $z_{rest} = 1.06$ confirms its thermal nature. We find that the CSS radio source is highly overpressured with respect to the thermal cluster medium by 2-3 orders of magnitude. This provides direct observational evidence that the radio source is not thermally confined as posited in the "frustrated" scenario for CSS sources. Instead, the radio source may be young and at an early stage of its evolution. This source provides the first detection of the AGN in outburst in the center of a cooling flow cluster. Powerful radio sources are thought to be triggered by the cooling flows. The evidence for the AGN activity and intermittent outbursts comes from the X-ray morphology of low redshift clusters, which usually do not harbour quasars. 3C186 is a young active radio source which can supply the energy into the cluster and potentially prevent its cooling. We discuss energetics related to the quasar activity and the cluster cooling flow, and possible feedback between the evolving radio source and the cluster.

Key words: quasars: individual (3C 186) - X-rays: galaxies: clusters.

1. INTRODUCTION

Quasars are luminous (L$_{tot} > 10^{45}$ erg sec^{-1}) and compact in the sense that the entire quasar luminosity originates within an unresolved core region (e.g. radius smaller than $r < 1$ pc). Large scale powerful outflows in a form of winds and jets are also observed. Such quasar activity is usually associated with an accretion process onto a supermassive black hole in the center of the a host galaxy (Silk & Rees 1998). This accretion process is not fully understood, however it is clear that a large fuel supply is needed to power a quasar. Where does the fuel come from and how quasars are born? The two scenarios involve a rich environment of clusters of galaxies: (1) a merger event can initiate a rapid fuel supply and efficient accretion; (2) large deposits of gas in the centers of cooling flow clusters can ignite the quasar (Fabian & Nulsen 1977).

There is a growing evidence for the past quasar activity in many X-ray clusters observed recently with *Chandra* X-ray Observatory. For example X-ray morphology of M87 in the Virgo cluster (Forman et al 2005) and Perseus A (Fabian et al 2003) shows large scale jets, signature of shocks and "bubbles" filled with radio plasma. Such X-ray morphology suggests a dissipation of energy into the cluster medium which prevents its cooling. Detailed studies of several clusters show the intermittent activity of a supermassive black hole of the central galaxy, with an average total outburst power reaching $\sim 10^{60}$ ergs. However, in all these systems the supermassive black hole of the cD galaxy is in the quiescence with the nucleus luminosity L$_{tot} < 10^{42}$ erg sec^{-1}. On the other hand one would expect that some powerful quasar should reside in clusters. Thus where are the clusters associated with the quasars?

Quasars are rare at low redshift, where most of X-ray clusters have been studied in details. The quasar density increases with redshift and in fact the quasars are seen in rich environment of clusters of galaxies in optical surveys (Ellingson, Yee & Green 1991). Over the last decade attempts have been made to find X-ray clusters associated with radio-loud quasars at high redshift. The limited capabilities of the available X-ray telescopes allowed only for a few detections of extended X-ray emission around radio sources at redshifts $z > 0.3$ (Hardcastle & Worrall 1999, Worrall et al. 2001, O'Dea et al 2000, Crawford

& Fabian 2003). High dynamic range observations are required to detect faint diffuse emission in the vicinity of a bright powerful source. Now *Chandra* can resolve spatially distinct X-ray emission components in the vicinity of a strong X-ray source with $\sim$1 arcsec resolution and a high dynamic range, as evidenced, for example, by the discovery of many resolved quasar X-ray jets (e.g. Schwartz et al. 2000, Siemiginowska et al. 2002, Sambruna et al. 2004, Marshall et al. 2005).

2. COMPACT RADIO SOURCES AND 3C 186 QUASAR

A large fraction of the radio source population is comprised of powerful compact sources (10-20%, O'Dea 1998). Their radio morphologies show a compact emission on arcsec (VLA resolution) scales while on milliarcsec scales (VLBI) the sources look remarkably like scaled down large radio galaxies, where the entire radio structure (1-10 kpc) is enclosed within the host galaxy. For more than a decade now there has been a clear controversy regarding their nature (see O'Dea 1998 and references therein). In the *evolution* model (Readhead et al. 1996a, 1996b) the source size and the characteristic spectral break at GHz radio frequencies could be an indication of young age, while in the other model the radio jet could be *frustrated* (Wilkinson et al. 1981, van Breugel et al. 1984) by a confining medium. Although recent studies give more weight to the *evolution* model there has been no definite observational evidence to rule out either of the models and both interpretations are still viable. Because these sources are very powerful one would expect that they reside in rich cluster environments. In either scenario the amount of fuel required to power a source is high, while in addition in the frustrated scenario the cluster medium should be dense enough to confine a radio source. Thus these compact radio may reside in clusters and therefore might be suitable candidates for detecting an X-ray cluster emission.

3C 186 is a luminous quasar ($L_{bol} \sim 10^{47}$ erg sec^{-1}). It has a strong big blue bump in the optical-UV band and broad optical emission lines (Simpson & Rawlings 2000, Kuraszkiewicz et al. 2002). It is therefore a typical quasar except for its radio properties. It is classified in radio as a compact steep spectrum (CSS) source. The radio morphology (Cawthorne et al 1986) shows two components separated by $2''$ and a jet connecting the core and NW component (Fig.1). No radio emission was reported on a larger scale. Based on the spectral age the estimated age of the radio source is $\sim 10^5$ years (Murgia et al. 1999).

3. CHANDRA OBSERVATIONS OF 3C 186

3C 186 was observed for $\sim$ 38 ksec with the *Chandra* Advanced CCD Imaging Spectrometer (ACIS-S, Weisskopf et al. 2002) on 2002 May 16 (ObsID 3098). The effective exposure time for this observation was 34,398 sec.

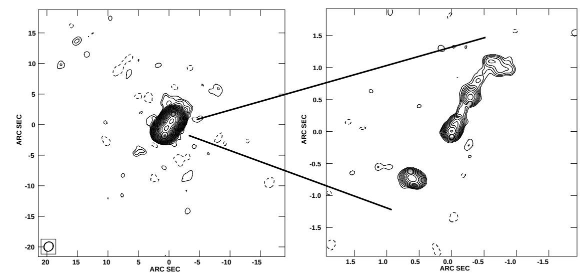

Figure 1. **Left:** *VLA 1.5 GHz image of 3C 186 The restoring beam is shown at the bottom left is 1.62" × 1.44" at PA=42.7 degrees. The image peak is 565 mJy/bm and contour levels begin at 0.5 mJy/beam (2σ) and increase by factors of $\sqrt{2}$. North is up East is left.* **Right:** *High resolution (0.15$''$) VLA 15 GHz image showing the 2" core-jet morphology. The image peak is 21.6 mJy/beam, and contours begin at 0.65 mJy/beam increasing by factors of $\sqrt{2}$.*

The 1/8 subarray CCD readout mode of one CCD only was used resulting in 0.441 sec frame readout time. Given the ACIS-S count rate of 0.025 counts s^{-1} frame^{-1} the pileup fraction was low $< 2\%$ (see PIMMS[1]). The X-ray data analysis was performed in CIAO 3.2[2] with the calibration files from the CALDB 3.0 data base. Spectral and image modeling and fitting was done in *Sherpa* (Freeman et al 2001). The details of the data analysis are presented elsewhere (Siemiginowska et al 2005).

3.1. X-ray Cluster at z=1.063

The *Chandra* observation reveals X-ray cluster emission at the redshift of the quasar 3C 186 (see Fig.2 and Fig.3). The cluster redshift is confirmed by the iron line detected in the spectrum of the diffuse emission. The X-ray properties of the cluster are summarized in Table 1. We compare the cluster temperature and its luminosity with results for the other clusters at high redshift using the `MEKAL` model with the abundance set to 0.3. The cluster temperature of $\sim 5.2^{+1.2}_{-0.9}$ keV and the total X-ray luminosity of $L_X(0.5-2\,\mathrm{keV}) \sim 6\times10^{44}$ erg sec^{-1} agree with the temperature-luminosity relation typically observed in high redshift ($z > 0.7$) clusters (e.g. Vikhlinin et al. 2002, Lumb et al. 2004). Based on the estimated cluster central electron density of approximately 0.044 ± 0.006 cm^{-3} for the best fit beta model parameters we infer the gas mass enclosed within 2 Mpc radius of $\sim 4.9^{\pm0.7}\times10^{13}M_\odot$ (the uncertainty only due to the uncertainty on electron density). This is about $\sim 6-10\%$ of the total cluster mass given the uncertainty on the cluster temperature and broadly agrees with the gas fraction usually found in high redshift (z>0.7) clusters. The estimated cooling time for the cluster core

[1] http://asc.harvard.edu/toolkit/pimms.jsp
[2] http://cxc.harvard.edu/ciao/

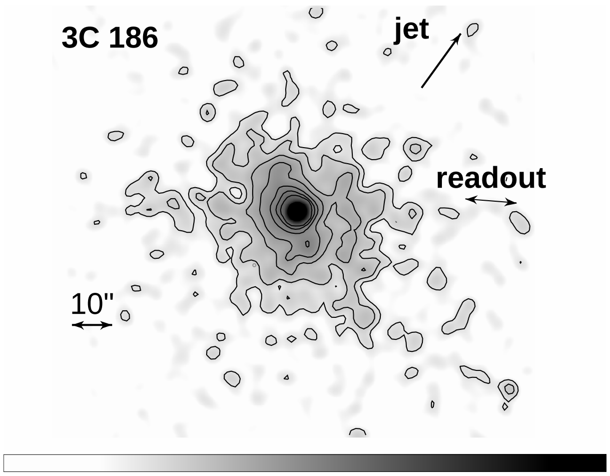

Figure 2. Adaptively smoothed exposure corrected image (photons energies within 0.3-7 keV range) of the Chandra ACIS-S observation of 3C 186 (Q0740+380). The diffuse emission is detected on $>$ 100 kpc scale, 1$''$=8.2 kpc. North is up and East is left. Contours represent a surface brightness of: (0.046,0.066, 0.13, 0.2, 0.33, 0.46, 0.66, 6.635, 33.175)$\times 10^{-6}$ photons cm^{-2} arcsec^{-2}. The direction of the CCD readout is indicated by arrow on the right side. An arrow in the upper right corner shows the PA=-37 deg of the 2$''$ radio jet (see Fig 1).

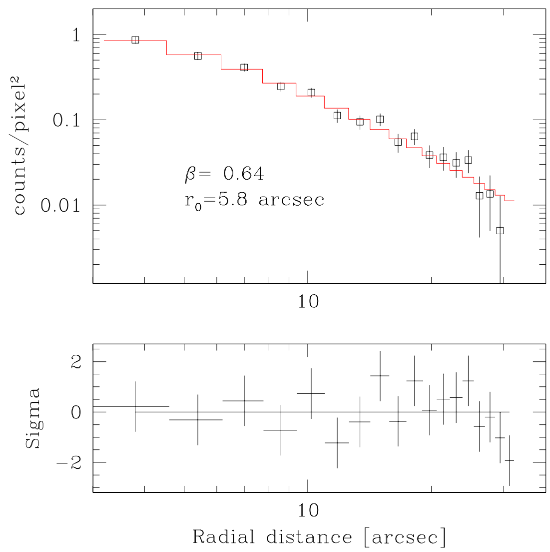

Figure 3. Background subtracted surface brightness profile for radii 3$''$ to 30$''$ fit with a beta model. The data are indicated by the square points. The solid line shows the best fit model with parameter $\beta = 0.64^{+0.11}_{-0.07}$ and a core radius of $r_{core} = 5.8''^{+2.1}_{-1.7}$. The bottom panel illustrates the differences between the data and the model in units of σ.

is $\sim 2.6 \times 10^9$ years which implies the cooling rate of ~ 50 M$_\odot$ year^{-1}.

3.2. Quasar in the Cluster

Based on the cluster central density and temperature, we estimate a central thermal pressure of the cluster medium to $\sim 5 \times 10^{-11}$ dyn cm^{-2}. If this pressure is higher than the pressure within the expanding radio components of the CSS source (Fig.1) then the cluster gas may be responsible for confining the radio source and its small size. Based on the radio measurements the minimum pressure in each radio component is of order $\sim 10^{-8}$ dyn cm^{-2}. Thus the radio source is highly overpressured by about 2-3 orders of magnitude with respect to the thermal cluster medium. This indicates that the hot gas cannot suppress the expansion and frustrate the jet, so the radio source is not confined, but it is at its early stage of the evolution into a large scale radio source.

The expansion of the radio source could potentially heat the cluster. The energy dissipated into the cluster by the expanding radio components has been widely discussed in the context of the low redshift clusters, where there is evidence for the repetitive outbursts of an AGN. However, the details of the dissipation process are still being studied (see Churazov review in this proceedings)

We can estimate the energy content of the hot cluster gas assuming a total emitting volume of 2.3×10^{71}cm^3

Table 1. Properties of the X-ray Cluster Emission.

Parameter	Property
β-model (1D)	β=0.64$^{+0.11}_{-0.07}$, r_c=5.8$^{+2.1}_{-1.7}$$''$
β-model (2D)	β=0.58$^{+0.06}_{-0.05}$, r_c=5.5$^{+1.5}_{-1.2}$$''$
	ellipticity = 0.24$^{+0.06}_{-0.07}$
	PA=47$\pm$10 degrees
$E_{\rm obs}$ (Fe-line)	3.18$\pm$0.07 keV
EW (Fe-line)	412 eV
$F_{\rm obs}$(0.5–2 keV)	6.2 $\pm$ 0.3 $\times$ 10^{-14} erg sec^{-1} cm^{-2}
$F_{\rm obs}$(2–10 keV)	5.0 $\pm$ 0.7 $\times$ 10^{-14} ergs sec^{-1} cm^{-2}
$F_{\rm nonthermal}$ (1 keV)	<5.4 $\times$ 10^{-15} erg sec^{-1} cm^{-2}
$L_{\rm tot}$(0.5–2 keV)	6$\times$ 10^{44} erg sec^{-1}
n$_e$	0.044$\pm$0.006 cm^{-3}
M$_{gas}$(r < 2Mpc)	4.9$\pm$0.7 $\times$ 10^{13} M$_\odot$

Fluxes are unabsorbed. Luminosities are K-corrected and in the source frame.

(contained by an annulus with 3 and 15″ radii, assuming spherical geometry) and $kT \sim 5$ keV, to be of the order of $\frac{3}{2}kTnV \sim 4.5{\times}10^{61}$ ergs (where n is the average gas particle density in the cluster). Assuming that the expanding radio source has been delivering the energy into the cluster at the current level of $L_{jet} \sim 10^{46}$erg sec^{-1} then the heating time is of the order of $\sim$$10^8$ years. We can also estimate the amount of mechanical work done by the jet and radio components during the expansion to the current radio size ($2'' \times 0.3'' \sim 2.3 \times 10^{66}$cm^3) as $pdV \sim 2 \times 10^{55}$ ergs. If the expansion velocity is of the order of $0.1c$ then the radio source has been expanding for about 5×10^5 years with an average power of $6{\times}10^{42}$ erg sec^{-1}. The estimated jet power is ~ 3 orders of magnitude higher.

The quasar optical-UV (big blue bump) luminosity of $5.7{\times}10^{46}$erg sec^{-1} (Simpson & Rawlings, 2000) is related to the accretion onto a supermassive black hole, so we can estimate the central black hole mass and required accretion rate. Assuming that the quasar is emitting at the Eddington luminosity the black hole mass should be of the order $\sim 4.5 \times 10^8$M$_\odot$. From CIV FWHM measurements of Kuraszkiewicz et al (2002) and the Vestergaard (2002) scaling relationship for the black holes, the estimated mass of the black hole is a factor of 10 higher, $\sim 3.2 \times 10^9$M$_\odot$. In any case the accretion rate required by the observed UV luminosity, assuming 10% radiation efficiency is equal to ~ 10 M$_\odot$year^{-1}. Given the age of the radio source of 5×10^5 years, a total of $\sim 5 \times 10^6$M$_\odot$ should have been accreted onto the black hole to support the current "outburst". This is only a small fraction of the mass involved in any merger events. Future detailed studies of the host galaxy and the optical field surrounding the quasar could provide more information on a population of galaxies and possible signatures of a merger.

4. SUMMARY

Chandra detected the X-ray cluster emission up to $\sim$ 120 kpc away from 3C 186, the CSS quasar at $z = 1.063$.

- There could be a cooling flow in the cluster, $t_{cool} \sim 1.6 \times 10^9$ years.
- This cluster is associated with the quasar, L$\sim$ 10^{47} erg sec^{-1}. Low redshift clusters show evidence of the past AGN outbursts, while their central AGN is typically quiet.
- Thermal pressure of the cluster gas is $\sim 2-3$ orders of magnitude lower than the pressure in the radio components. Hot cluster gas does not confine the jet.
- Future XMM observations would allow for studying a large scale cluster emission.
- Deep optical imaging could provide details on properties of the host galaxy and the population of galaxies in this high redshift cluster at the early stage of its formation.

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